AD-A147 711 LUMPED CIRCUIT TRANSMISSION LINE MODEL(U) ROME AIR DEVELOPMENT CENTER GRIFFISS AFB NY D H COLVIN JUN 84 RADC-TR-84-148 1/1

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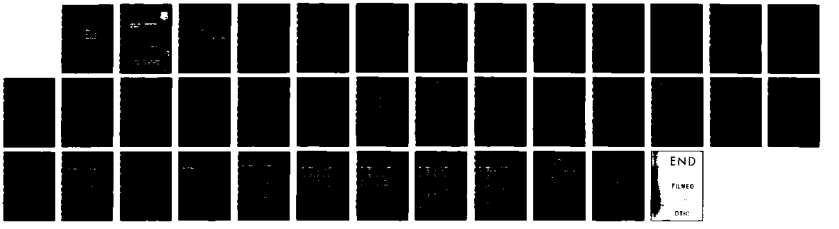

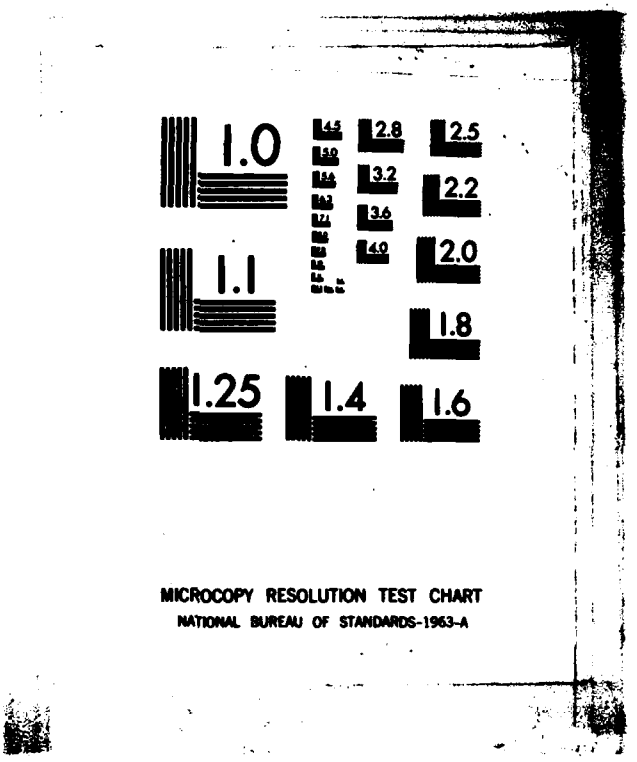

RADC-TR-84-148
In-House Report
June 1984

LUMPED CIRCUIT TRANSMISSION LINE MODEL

Douglas H. Colvin

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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APPROVED: Samuel D. Zaccari

SAMUEL D. ZACCARI, Chief
Compatibility & Measurements Branch
Reliability & Compatibility Division

APPROVED: W. S. Tuthill

W. S. TUTHILL, Colonel, USAF
Chief, Reliability & Compatibility Division

FOR THE COMMANDER: John A. Ritz

JOHN A. RITZ
Acting Chief, Plans Office

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: N/A
2a. SECURITY CLASSIFICATION AUTHORITY: N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): RADC-TR-84-148	5. MONITORING ORGANIZATION REPORT NUMBER(S): N/A
6a. NAME OF PERFORMING ORGANIZATION: Rome Air Development Center; 6b. OFFICE SYMBOL (If applicable): RBCT	7a. NAME OF MONITORING ORGANIZATION: N/A
6c. ADDRESS (City, State and ZIP Code): Griffiss AFB NY 13441	7b. ADDRESS (City, State and ZIP Code):
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Rome Air Development Center; 8b. OFFICE SYMBOL (If applicable): RBCT	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N/A
8c. ADDRESS (City, State and ZIP Code): Griffiss AFB NY 13441	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62702F	2338	03	20

11. TITLE (Include Security Classification): LUMPED CIRCUIT TRANSMISSION LINE MODEL

12. PERSONAL AUTHOR(S): Douglas H. Colvin

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
In-House	FROM 1983 TO 1984	June 1984	40

16. SUPPLEMENTARY NOTATION: N/A

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Lumped Circuit Model, Transmission Line, Z-Parameters, Network Synthesis, "T" Network
09	03		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The primary objective of this work has been to derive a lumped circuit model for the lossless (or low loss) transmission line which yields accurate output voltages regardless of the type of line termination. The model is developed by synthesizing a lumped circuit exhibiting Z-parameters which are the same as those for the distributed parameter transmission line.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☑ SAME AS RPT. ☐ DTIC USERS ☐	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Douglas H. Colvin	(315) 330-2563	RADC (RBCT)

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

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Lumped Circuit Transmission Line Model

INTRODUCTION

Several computer aided design (CAD) programs require lumped circuit component values (resistors, inductors, and capacitors) as input data. It is often difficult, if not impossible, for a user of these CAD programs to mix distributed and lumped circuit parameters. Lumped circuit equivalents of distributed circuits are desired for sake of compatibility.

Transmission line responses are governed by distributed parameters. In this report, the development of a lumped circuit model for the lossless transmission line is performed by deriving its Z-parameter expressions and then synthesizing these parameters with lumped circuit equivalents.

If the Z-parameters are accurately synthesized, the model will be virtually insensitive to source or load impedances. Two forms of Z-parameter networks are possible: the "T" network and the " Π " network. In this report, the "T" network is employed.

THE DISTRIBUTED PARAMETER TRANSMISSION LINE (DPTL)

This section describes the necessary equations needed to work with the lossless DPTL. The dominant mode for the propagation of signals is assumed to be transverse electromagnetic (TEM) in which both the electric and magnetic fields are transverse (perpendicular) to the axis of the transmission line. Also, the DPTL is assumed to be uniform and the medium of propagation is

assumed to be homogeneous.

Voltages and currents at any point along the line can be determined if the total voltage and current are known at the sending and receiving ends of that line. Corresponding to Figure 1, we have [1]

$$
\begin{aligned}
V_S &= V_R \cosh \gamma \ell + I_R Z_0 \sinh \gamma \ell \\
V_R &= V_S \cosh \gamma \ell - I_S Z_0 \sinh \gamma \ell \\
I_S &= I_R \cosh \gamma \ell + (V_R/Z_0) \sinh \gamma \ell \\
I_R &= I_S \cosh \gamma \ell - (V_S/Z_0) \sinh \gamma \ell
\end{aligned}
\qquad (1)
$$

where, Z_0 = characteristic impedance

γ = propagation constant

and other quantities are defined in Figure 1.

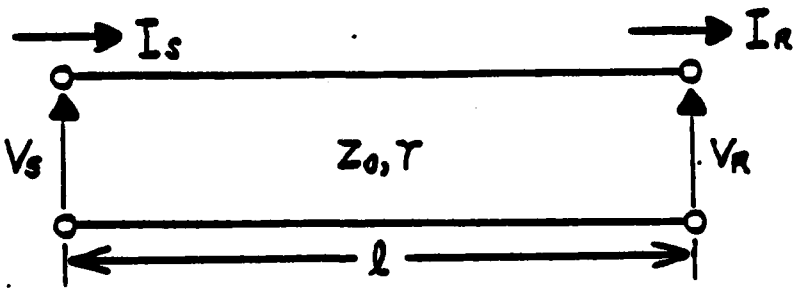


Figure 1

The characteristic impedance and propagation constant are typically expressed as

$$Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \qquad \gamma = \sqrt{(R+j\omega L)\ (G+j\omega C)} \tag{2}$$

where, R = resistance per unit length

L = inductance per unit length

G = conductance per unit length

C = capacitance per unit length

If R and G are assumed to be negligible, as for the lossless line, equation (2) becomes

$$Z_0 = \sqrt{\frac{L}{C}} \quad , \quad \gamma = jw\sqrt{LC} \quad \triangleq \quad j\beta \tag{3}$$

and substitution into equation (1) yields

$$\begin{aligned} V_S &= V_R \cos \beta\ell + jI_R Z_0 \sin \beta\ell \\ V_R &= V_S \cos \beta\ell - jI_S Z_0 \sin \beta\ell \\ I_S &= I_R \cos \beta\ell + j(V_R/Z_0) \sin \beta\ell \\ I_R &= I_S \cos \beta\ell - j(V_S/Z_0) \sin \beta\ell \end{aligned} \tag{4}$$

The equations in (4) are the only ones required to find the Z parameters of the lossless DPTL.

Z-PARAMETERS FOR THE LOSSLESS DPTL

The symmetric and reciprocal DPTL may be fully described by a "T" network incorporating the Z-parameters shown in Figure 2.

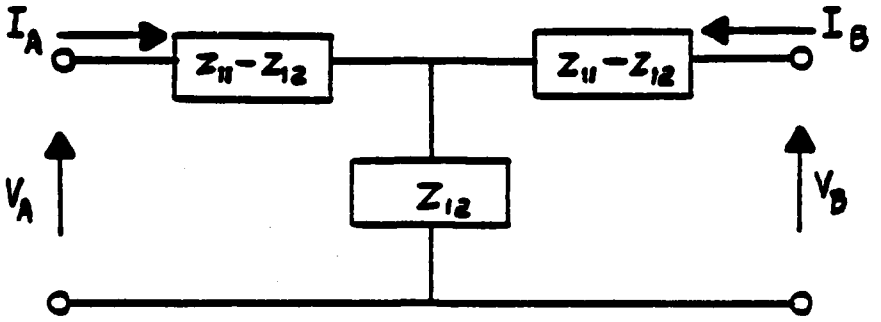


Figure 2

The input and output voltages are determined from

$$V_A = Z_{11}\, I_A + Z_{12}\, I_B$$

$$V_B = Z_{21}\, I_A + Z_{22}\, I_B \qquad (5)$$

Since we have symmetry and reciprocity, $Z_{21} = Z_{12}$ and $Z_{22} = Z_{11}$ so that (5) becomes

$$V_A = Z_{11} I_A + Z_{12} I_B$$
$$V_B = Z_{12} I_A + Z_{11} I_B \qquad (6)$$

The equations in (4) may be manipulated so that V_S and V_R are in terms of I_S and I_R. Upon doing this, we have

$$V_S = -jI_S Z_0 \cot \beta\ell + jI_R Z_0 \csc \beta\ell$$
$$V_R = -jI_S Z_0 \csc \beta\ell + jI_R Z_0 \cot \beta\ell \qquad (7)$$

When these equations for V_S and V_R are compared to the equations in (6), we can see that we have the relationships between the Z-parameters and the DPTL parameters:

$$Z_{11} = -jZ_0 \cot \beta\ell,\ Z_{12} = -jZ_0 \csc \beta\ell$$
$$\text{and } Z_{11} - Z_{12} = jZ_0 \tan \beta\ell/2$$

The DPTL may now be represented by the network shown in Figure 3.

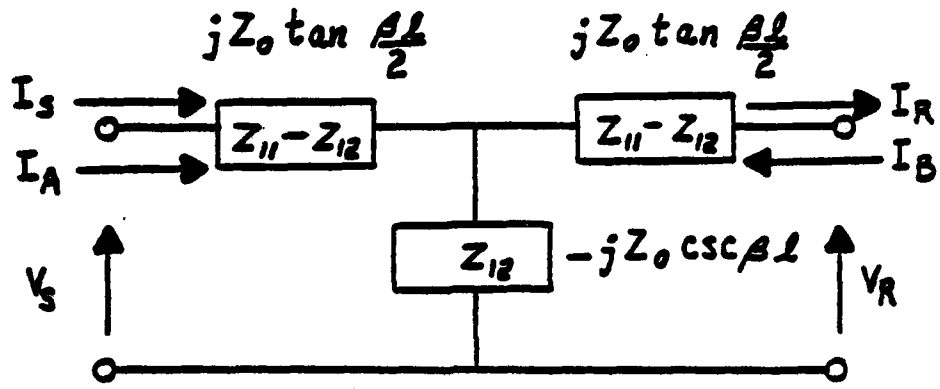


Figure 3

The remaining task is to find circuits which will represent the impedances $jZ_0 \tan \beta\ell/2$ and $-jZ_0 \csc \beta\ell$ to a high degree of accuracy. The techniques used are discussed in the next section.

CIRCUIT SYNTHESIS

The impedances, $Z_{11}-Z_{12}$ and Z_{12}, will be synthesized separately. Since these impedances are trigonometric functions, it is suitable to express the sine and cosine in terms of polynomial expansions. (2)

$$\sin X = X\,(1 + a_2 X^2 + a_4 X^4 + a_6 X^6 + a_8 X^8 + a_{10} X^{10}) + |\varepsilon_a|$$
$$|\varepsilon_a| \leq 2\times10^{-9} \quad , \quad 0 \leq X \leq \pi/2$$

$$\cos X = 1 + b_2 X^2 + b_4 X^4 + b_6 X^6 + b_8 X^8 + b_{10} X^{10} + |\varepsilon_b|$$
$$|\varepsilon_b| \leq 2\times10^{-9}, \quad 0 \leq X \leq \pi/2 \qquad (8)$$

$$\csc X = \frac{1}{X} + 2X \sum_{n=1}^{\infty} \frac{(-1)^n}{X^2-(n\pi)^2} \qquad (9)$$

where:

$a_2 = -.1666666664$	$b_2 = -.4999999963$
$a_4 = .0083333315$	$b_4 = .0416666418$
$a_6 = -.0001984090$	$b_6 = -.0013888397$
$a_8 = .0000027526$	$b_8 = .0000247609$
$a_{10} = -.0000000239$	$b_{10} = -.0000002605$

Equations in (8) are used for $jZ_0 \tan \beta\ell/2$, and equation (9) is used for $-jZ_0 \csc \beta\ell$. First, we will synthesize the impedance, $jZ_0 \tan \beta\ell/2$, then we will work on $jZ_0 \csc \beta\ell$.

SYNTHESIS OF $Z_{11} - Z_{12}$

It can be shown that $\beta\ell/2 = -jKs$ where $K = \frac{\ell\sqrt{\mu\varepsilon}}{2}$ and $s = j\omega$. Now we may write $jZ_0 \tan \beta\ell/2$ as $jZ_0 \tan(-jKs)$. Using equations in (8), we get:

$$jZ_0\tan(-jKs) = jZ_0\left[\frac{-jKs\{1+a_2(-jKs)^2+a_4(-jKs)^4+\cdots+a_{10}(-jKs)^{10}\}}{1+b_2(-jKs)^2+b_4(-jKs)^4+\cdots+b_{10}(-jKs)^{10}}\right]$$

$$= \frac{Z_0Ks - a_2Z_0K^3s^3 + a_4Z_0K^5s^5 - a_6Z_0K^7s^7 + a_8Z_0K^9s^9 - a_{10}Z_0K^{11}s^{11}}{1 - b_2K^2s^2 + b_4K^4s^4 - b_6K^6s^6 + b_8K^8s^8 - b_{10}K^{10}s^{10}}$$

(10)

$$\triangleq \frac{N(s)}{D(s)}$$

Synthetic division of (10) is performed in a manner shown in equation (11) which yields a network of a Cauer form (Figure 4). See Appendix A.

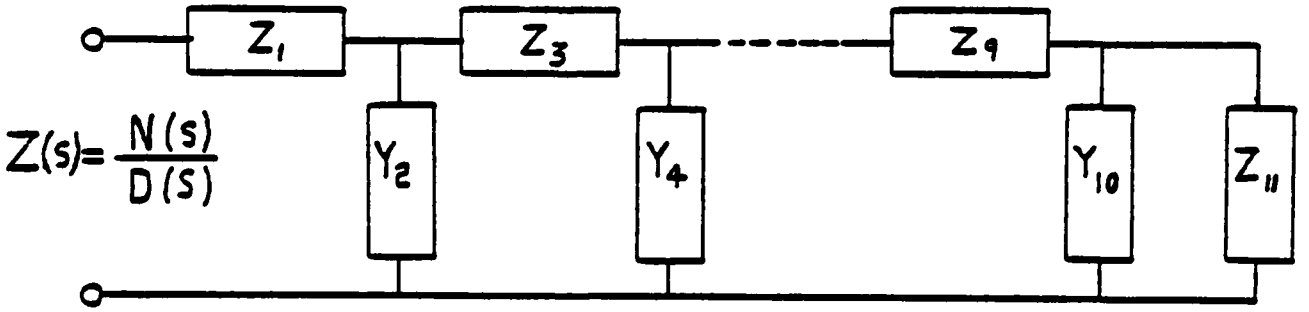


Figure 4

$$\frac{N(s)}{D(s)} = \cfrac{Z_1}{Y_2 + \cfrac{1}{Z_3 + \cfrac{1}{Y_4 + \cfrac{1}{\ddots}}}} \qquad (11)$$

Once the synthetic division is complete, we can find the corresponding circuit elements.

$L_1 = .09174664 Z_0 K$ $\qquad$ $C_2 = .5417253 K/Z_0$

$L_3 = -.03511307 Z_0 K$ $\qquad$ $C_4 = -.04033142 K/Z_0$

$L_5 = .07935383 Z_0 K$ $\qquad$ $C_6 = .2536086 K/Z_0$

$L_7 = .7765806 Z_0 K$ $\qquad$ $C_8 = -.05267314 K/Z_0$

$L_9 = -.2371512 Z_0 K$ $\qquad$ $C_{10} = .5358672 K/Z_0$

$L_{11} = .3245832 Z_0 K$

where L is in Henrys and C is in Farads.

Figure 5 shows the completed circuit whose port impedance is $jZ_0 \tan \beta\ell/2$.

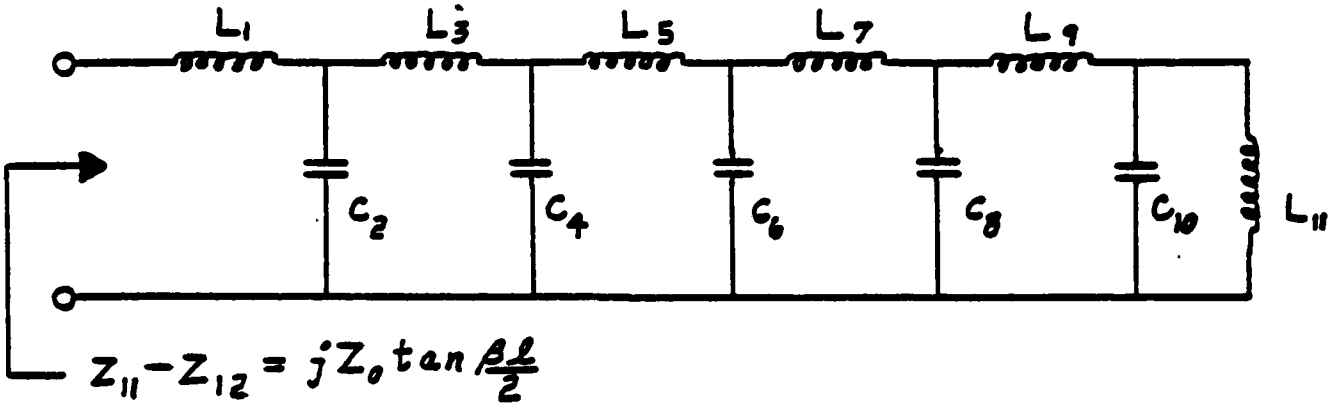


Figure 5

SYNTHESIS OF Z_{12}

For the synthesis of $Z_{12} = -jZ_0 \csc \beta\ell$, we use the expansion form of equation (9) but instead of an infinite summation, we will use N terms. Letting $x = \beta\ell = -j2Ks$, we get

$$-jZ_0 \csc \beta\ell = -jZ_0 \left[\frac{1}{-j2Ks} + 2(-j2Ks) \sum_{n=1}^{N} \frac{(-1)^n}{(-j2Ks)^2 - (n\pi)^2} \right]$$

which may be rearranged into

$$-jZ_0 \csc \beta\ell = \frac{Z_0}{2Ks} + \sum_{n=1}^{N} \frac{(-1)^n 4Z_0 Ks}{4K^2s^2 + (n\pi)^2} \qquad (12)$$

The addend of equation (12) is of the form $\frac{as}{bs^2+c}$ which is a general impedance expression of an LC tank circuit.

Consider the tank circuit of Figure 6; its terminal impedance is given by

$$Z(s) = \frac{sL}{LCs^2+1}$$

which can be forced to equal the addend of (12). By doing this we find that

$$L_n = \frac{(-1)^n 4Z_0 K}{(n\pi)^2} \quad , \quad C_n = \frac{K}{(-1)^n Z_0}$$

The first term of (12) is the impedance of a capacitor whose value is $2K/Z_0$. Now the synthesized circuit for Z_{12} is complete and shown in Figure 7.

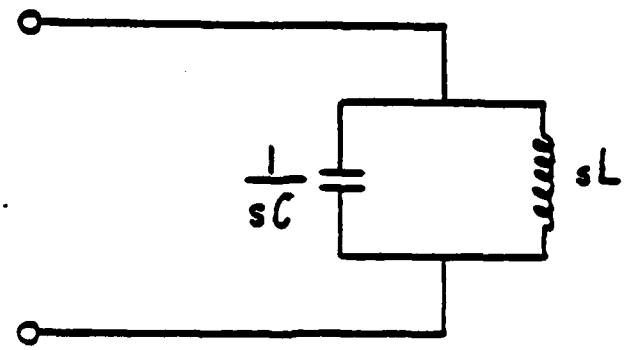
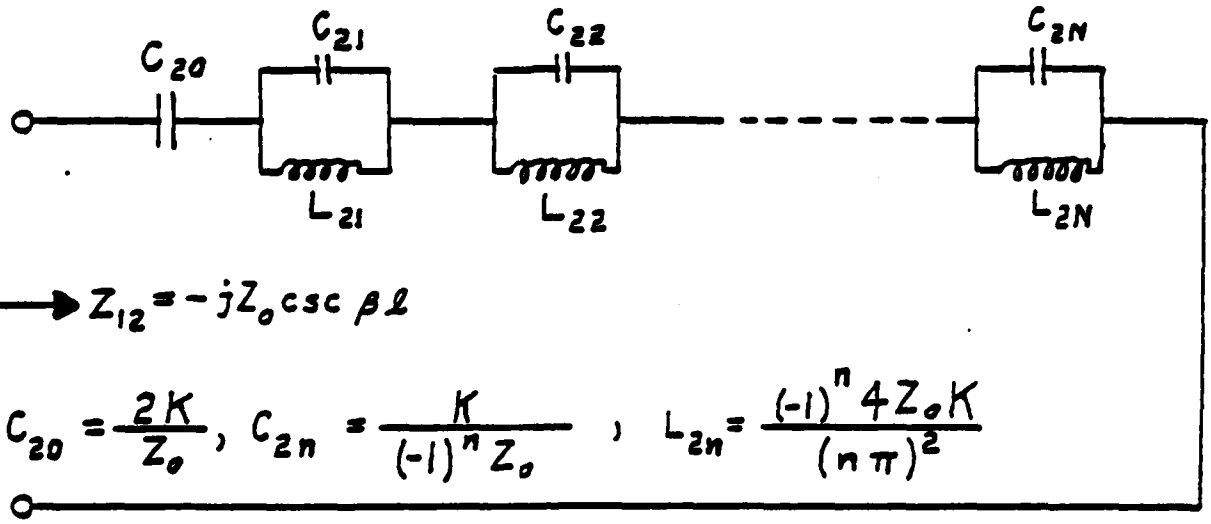


Figure 6



$$\longrightarrow Z_{12} = -jZ_0 \csc \beta \ell$$

$$C_{20} = \frac{2K}{Z_0}, \quad C_{2n} = \frac{K}{(-1)^n Z_0}, \quad L_{2n} = \frac{(-1)^n 4 Z_0 K}{(n\pi)^2}$$

Figure 7

THE COMPLETED MODEL AND ITS ANALYSIS

By placing the networks of Figure 5 and Figure 7 into the Z-parameter network of Figure 2, the complete model for the DPTL is developed. Shown in Figure 8 is the model's schematic along with the source and load impedances.

A Fortran Program (Appendix B) has been written in order that the DPTL model may be analyzed for errors in the output voltage. In the program, "MVOD" is the magnitude of V_S/V_L (See Figure 8) as determined by the use of the standard transmission line equations and "MVOL" is the magnitude of V_S/V_L as determined by the DPTL model. The error (in dB) (See Figure 9) is defined as

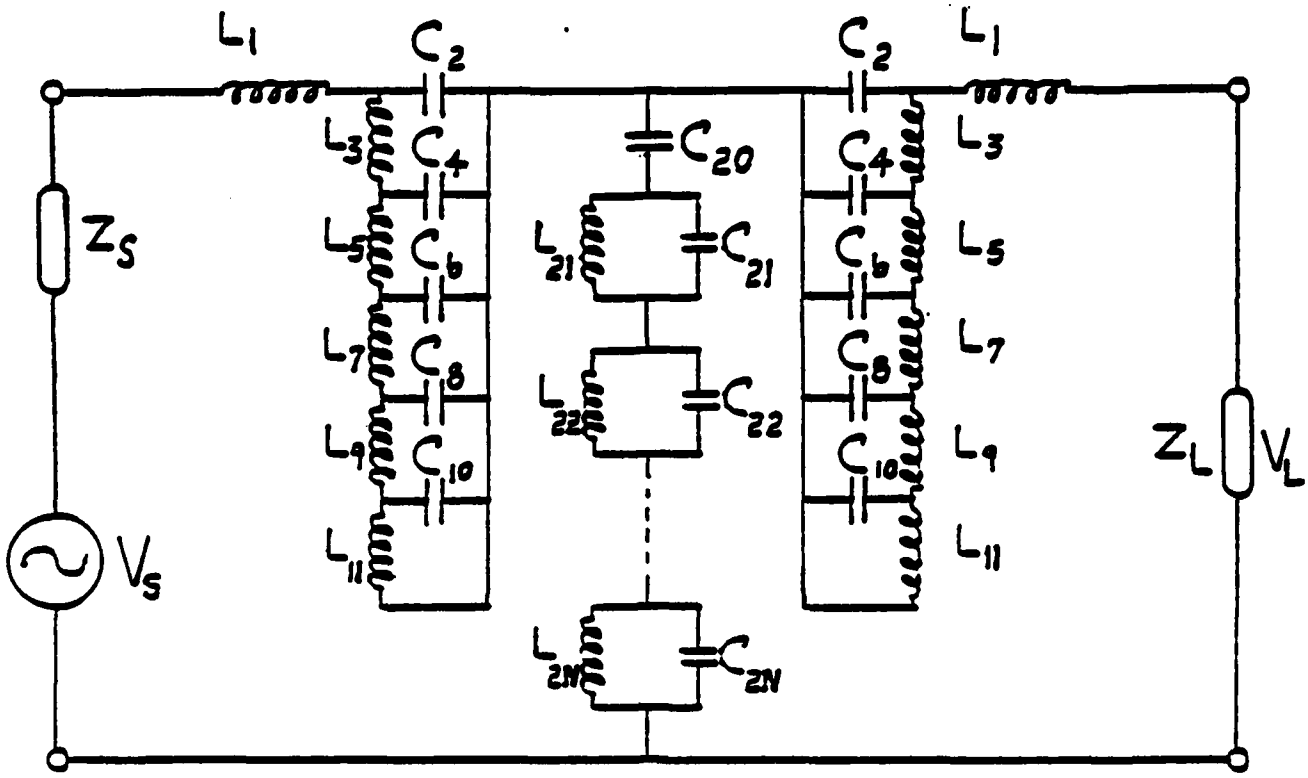
$$\text{Error}_{dB} = 20 \text{ Log } (\text{MVOL}/\text{MVOD})$$

Resonances along the line are very evident. The errors at $\lambda/4$ and $3\lambda/4$ are seen to be small compared to those at $\lambda/2$ and λ. This is because the approximations of equation (8) are in greatest error at $x = \pi/2$ and least error at $x=0$ and $x=\pi/4$. The huge error at line lengths of $\lambda/2$ and λ are not troublesome if one does not include frequencies which correspond to line lengths equal to <u>exactly</u> $\lambda/2$ and λ.

Conclusion and Recommendations

The sample runs in Appendix B are for transmission lines with

LOSSLESS DPTL MODEL



$L_1 = .04587332KZ_o$
$L_3 = .01755653KZ_o$
$L_5 = .03967702KZ_o$
$L_7 = .38828470KZ_o$
$L_9 = .11857035KZ_o$
$L_{11} = .16229000KZ_o$

$C_{20} = 2K/Z_o$
$C_2 = .27086255K/Z_o$
$C_4 = .02016570SK/Z_o$
$C_6 = .12680405K/Z_o$
$C_8 = .02633792K/Z_o$
$C_{10} = .26795260K/Z_o$

$$L_{2n} = (-1)^n \frac{2KZ_o}{(n\pi)^2}$$

$$C_{2n} = (-1)^n \frac{K}{2Z_o}$$

$$K = \frac{\beta l}{\omega}$$

Figure 8

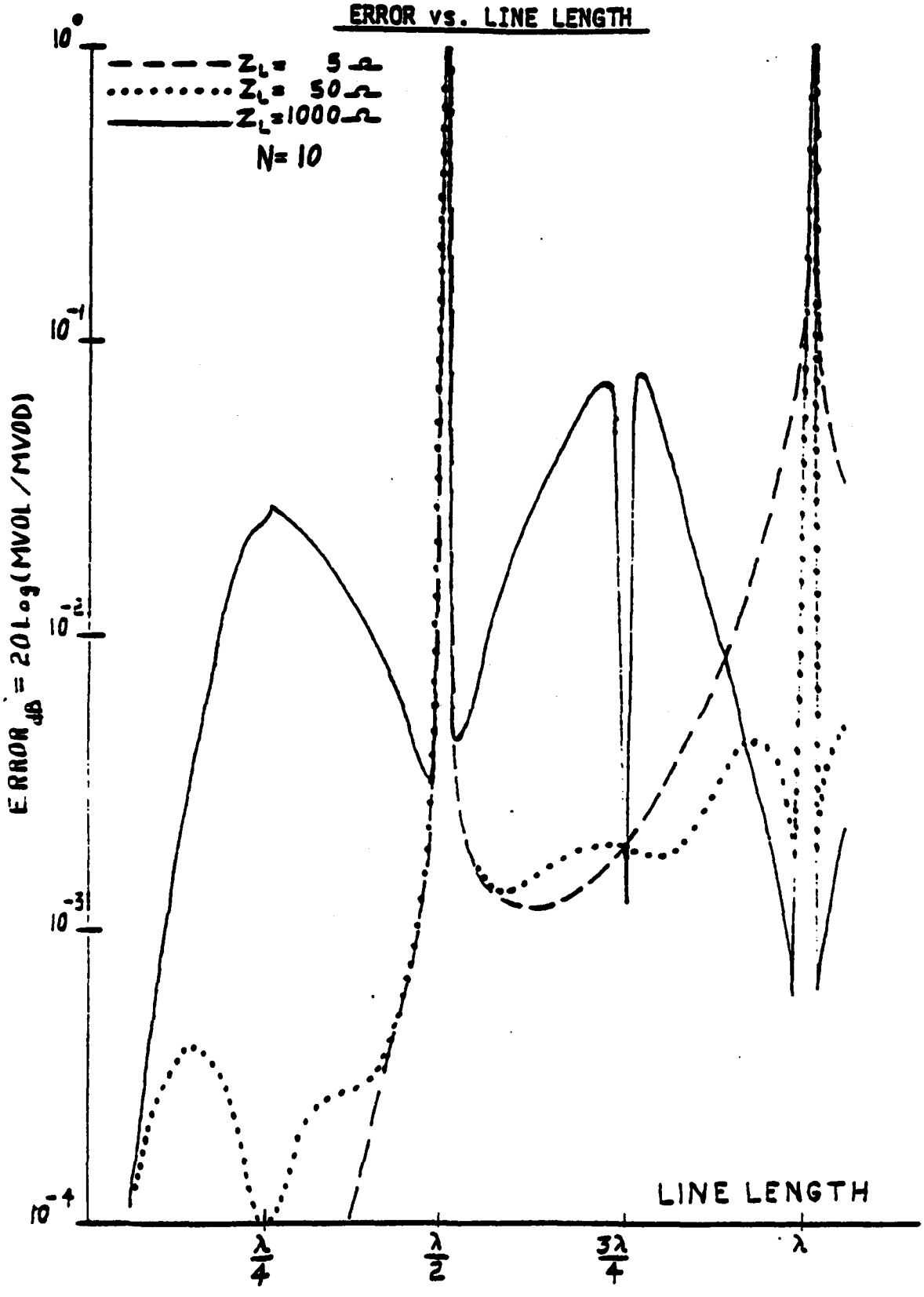

ERROR vs. LINE LENGTH
Z_L= 5Ω
Z_L= 50Ω
Z_L=1000Ω
N= 10
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$ERROR_{dB} = 20Log(MVOL/MVOD)$
LINE LENGTH
$\frac{\lambda}{4}$
$\frac{\lambda}{2}$
$\frac{3\lambda}{4}$
λ

Figure 9

relative permittivity (ϵ_r) equal to one. The program allows one to input other values of ϵ_r; but then, the effective line length will be different.

The errors between calculations from the DPTL model and the transmission line equations are less than one-tenth decibel provided the effective line length is less than or equal to one wavelength. The load, Z_L, does not significantly affect the results unlike the case of typical lumped circuit models [4].

The use of the DPTL model may be found for several applications where line losses are low. When losses are high, this model can no longer be used. Thus, it is recommended that a similar model which considers losses be developed. It is also desirable to test the present DPTL model using nonlinear sources and loads. Once the models for the lossy lines are developed, coupling and cross-talk can be considered next for modeling in terms of lumped circuit components.

APPENDIX A

The Cauer Network

The synthesis considered here is that for the one-port network. Here, Cauer's method [3] is used. Cauer networks are derived from the expansion of a rational fraction (equation (A-1)) into the Stieljes' continued fraction expansion (equation (A-2)) which is the same as equation (11).

$$R(s) = \frac{N(s)}{D(s)} = \frac{A_0 s^m + A_1 s^{m-1} + A_2 s^{m-2} + \cdots\cdots}{B_0 s^n + B_1 s^{n-1} + B_2 s^{n-2} + \cdots\cdots} \qquad \text{(A-1)}$$

Stieljes' continued fraction expansion of (A-1) is

$$R(s) = C_0 s^{m-n} + \cfrac{1}{C_1 s^{m-n} + \cfrac{1}{C_2 s^{m-n} + \cfrac{1}{C_3 s^{m-n} + \cfrac{1}{\ddots}}}} \qquad \text{(A-2)}$$

R(s) has been used to denote either a driving-point impedance, Z(s), or a driving-point admittance, Y(s).

Depending on the values of the A's and B's, some of the capacitances and inductances may have negative values; this should not disturb anyone since the network is not to be realized. Note that if the network is not to be necessarily realizable, we may consider two possible relationships between m and n of equation (A-1).

$$
\begin{array}{lll}
m=n+1 & R(s)=Z(s) : & C_0 s, C_2 s, C_4 s, \ldots\ldots = \text{inductive reactances} \\
 & & C_1 s, C_3 s, C_5 s, \ldots\ldots = \text{capacitive reactances} \\
 & R(s)=Y(s) : & C_0 s, C_2 s, C_4 s, \ldots\ldots = \text{capacitive reactances} \\
 & & C_1 s, C_3 s, C_5 s, \ldots\ldots = \text{inductive reactances} \\
m=n-1 & R(s)=Z(s) : & C_0/s, C_2/s, C_4/s, \ldots\ldots = \text{capacitive reactances} \\
 & & C_1/s, C_3/s, C_5/s, \ldots\ldots = \text{inductive reactances} \\
 & R(s)=Y(s) : & C_0/s, C_2/s, C_4/s, \ldots\ldots = \text{inductive reactances} \\
 & & C_1/s, C_3/s, C_5/s, \ldots\ldots = \text{capacitive reactances}
\end{array}
\qquad \text{(A-3)}
$$

For equation (10), m = n+1 is used:

$$
Z(s) = \frac{A_0 s + A_1 s^2 + A_2 s^3 + \ldots + A_{10} s^{11}}{B_0 + B_1 s + B_2 s^2 + \ldots + B_{10} s^{10}}
$$

which yields the network shown in Figure 4.

APPENDIX B

PROGRAM LISTING

```
LIST TLINE

10 COMPLEX Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,ZINS,TQ,P
20 COMPLEX ZZ1,ZZ2,UU,DN1,DN2,DN3,DN4,DN5,DN,VOD,ZS,ZL,Z0
25 COMPLEX ZINP,UN,DEN1,DEN2,DEN3,DEN4,DEN5,DEN,VOL,T9
30 REAL F,PI,W,LENG,EP,C,F0,F1,F2,LOL
35 REAL Q,QT,T1,T2,T3,T4,T5,T6,FA,SUM
40 REAL BL,BL2,T7,T8,MVOL,MVOD
70 Z0=CMPLX(50.,0.)
72 ZS=CMPLX(10.,-25.)
74 ZL=CMPLX(200.,500.)
80 PI=3.14159265
90 LENG=1.
110 EP=1.
112 WRITE(6,77)LENG,EP
114 77 FORMAT("LENGHT= ",F12.5,3X,"EPSILON= ",F12.5)
116 WRITE(6,76)Z0
117 WRITE(6,75)ZS,ZL
118 76 FORMAT("Z0= ",2E12.5)
119 75 FORMAT("ZS= ",2E12.5,3X,"ZL= ",2E12.5)
120 C=3.E8
122 DO 100 N=10,10000,50
124 F=(FLOAT(N))*1.E6
126 W=2.*PI*F
130 LOL=LENG*F*SQRT(EP)/(3.E8)
140 F0=PI*LOL/W
150 F1=Z0*F0
160 F2=F0/Z0
170 T=W*F1*.0917466
180 Z1=CMPLX(0.,T)
190 T=-1./(W*F2*.5417253)
200 Z2=CMPLX(0.,T)
210 T=W*F1*(-.0351131)
220 Z3=CMPLX(0.,T)
230 T=1./(W*F2*.4033141)
240 Z4=CMPLX(0.,T)
250 T=W*F1*(.0793403)
260 Z5=CMPLX(0.,T)
270 T=-1./(W*F2*.2536081)
280 Z6=CMPLX(0.,T)
290 T=W*F1*.7765694
300 Z7=CMPLX(0.,T)
310 T=1./(W*F2*.05267584)
320 Z8=CMPLX(0.,T)
330 T=-1.*W*F1*.2371407
340 Z9=CMPLX(0.,T)
350 T=-1./(W*F2*.5359052)
```

```
360 Z10=CMPLX(0.,T)
370 T=W*PI*.3245E
380 Z11=CMPLX(0.,T)
390 P=Z9+Z10*Z11/(Z10+Z11)
400 P=Z7+Z8*P/(Z8+P)
410 P=Z5+Z6*P/(Z6+P)
420 P=Z3+Z4*P/(Z4+P)
430 ZINS=Z1+Z2*P/(Z2+P)
440 Q=PI*LOL
450 QT=Z0*TAN(Q)
460 TQ=CMPLX(0.,QT)
470 T1=4.*EP*LOL*LOL
480 T2=(4./PI)*LOL*SQRT(EP)
485 T3=1./(2.*PI*LOL*SQRT(EP))
487 SUM=0.
488 FA=-1.
490 DO 99 I=1,20
500 T5=(FLOAT(I))**2-T1
505 T6=FA/T5
510 SUM=T6+SUM
515 FA=-1.*FA
520 99 CONTINUE
522 SUM=T3-T2*SUM
525 SUM=-1.*Z0*SUM
530 ZINP=CMPLX(0.,SUM)
535 UN=ZL*ZINP
540 DEN1=ZS+ZL
545 DEN2=ZINS+ZINP
550 DEN3=ZS*ZL
555 DEN4=ZINS*ZINP*CMPLX(2.,0.)
560 DEN5=ZINS*ZINP
565 DEN=DEN1*DEN2+DEN3+DEN4+DEN5
580 VOL=UN/DEN
582 MVOL=CABS(VOL)
585 BL=LOL*PI*2.
590 BL2=BL/2.
600 T7=TAN(BL2)
605 T8=-1./SIN(BL)
608 T9=CMPLX(0.,T8)
610 ZZ2=T9*Z0
615 ZZ1=Z0*CMPLX(0.,T7)
620 UU=ZL*ZZ2
625 DN1=ZS+ZL
630 DN2=ZZ1+ZZ2
635 DN3=ZS*ZL
640 DN4=ZZ1*ZZ2*CMPLX(2.,0.)
```

```
645 DN5=ZZ1*ZZ2
650 DN=DN1*DN2+DN3+DN4+DN5
655 VOD=UU/DN
657 MVOD=CABS(VOD)
800 WRITE(6,1)F,LOL
830 WRITE(6,2)VOL,VOD
835 WRITE(6,3)MVOL,MVOD
840 1 FORMAT("FREQ.= ",E12.5,3X,"LEN/LAM= ",E12.5)
850 2 FORMAT("VOL= ",2E12.5,3X,"VOD= ",2E12.5)
855 3 FORMAT("MVOL= ",E12.5,3X,"MVOD= ",E12.5)
858 WRITE(6,4)
859 4 FORMAT("==========================================")
860 100 CONTINUE
870 STOP
880 END
```

Output Samples

```
RUN TLINE

LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 01 0.                    ZL=  0.10000E 01 0.
FREQ.=  0.10000E 09    LEN/LAM=  0.33333E-01
VOL=  0.77473E-02-0.62452E-01    VOD=  0.77473E-02-0.62451E-01
MVOL=  0.62930E-01    MVOD=  0.62930E-01
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.51984E-04-0.91740E-02    VOD=  0.52017E-04-0.91740E-02
MVOL=  0.91742E-02    MVOD=  0.91741E-02
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.11801E-04-0.29680E-02    VOD= -0.11789E-04-0.29680E-02
MVOL=  0.29680E-02    MVOD=  0.29680E-02
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.96015E-06 0.70077E-03    VOD= -0.96048E-06 0.70069E-03
MVOL=  0.70077E-03    MVOD=  0.70069E-03
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.14432E-04 0.48435E-02    VOD= -0.14497E-04 0.48431E-02
MVOL=  0.48435E-02    MVOD=  0.48431E-02
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.30019E-03 0.14969E-01    VOD=  0.29980E-03 0.14964E-01
MVOL=  0.14972E-01    MVOD=  0.14967E-01
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.77040E-02-0.62281E-01    VOD=  0.77473E-02-0.62451E-01
MVOL=  0.62756E-01    MVOD=  0.62930E-01
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.53130E-04-0.92286E-02    VOD=  0.52017E-04-0.91740E-02
MVOL=  0.92288E-02    MVOD=  0.91741E-02
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.11128E-04-0.32494E-02    VOD= -0.11789E-04-0.29680E-02
MVOL=  0.32494E-02    MVOD=  0.29680E-02
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.22767E-05-0.57938E-03    VOD= -0.96048E-06 0.70069E-03
MVOL=  0.57938E-03    MVOD=  0.70069E-03
================================================================
```

RUN TLINE

```
LENGHT=       1.00000    EPSILON=       1.00000
Z0=  0.50000E 02 0.
ZS=  0.10000E 01 0.                    ZL=  0.50000E 02 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.90909E 00-0.29109E 00    VOD=  0.90909E 00-0.29109E 00
MVOL=  0.95455E 00    MVOD=  0.95455E 00
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.63851E-01-0.44568E 00    VOD=  0.63890E-01-0.44567E 00
MVOL=  0.45023E 00    MVOD=  0.45022E 00
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.14830E-01-0.14658E 00    VOD= -0.14815E-01-0.14659E 00
MVOL=  0.14733E 00    MVOD=  0.14733E 00
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.12224E-02 0.34991E-01    VOD= -0.12223E-02 0.34987E-01
MVOL=  0.35012E-01    MVOD=  0.35008E-01
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.18133E-01 0.23972E 00    VOD= -0.18213E-01 0.23969E 00
MVOL=  0.24040E 00    MVOD=  0.24038E 00
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.29834E 00 0.58977E 00    VOD=  0.29807E 00 0.58981E 00
MVOL=  0.66094E 00    MVOD=  0.66085E 00
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.90867E 00-0.29179E 00    VOD=  0.90909E 00-0.29109E 00
MVOL=  0.95437E 00    MVOD=  0.95455E 00
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.55209E-01-0.44801E 00    VOD=  0.53890E-01-0.44567E 00
MVOL=  0.45273E 00    MVOD=  0.45022E 00
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.14016E-01-0.16087E 00    VOD= -0.14815E-01-0.14659E 00
MVOL=  0.16148E 00    MVOD=  0.14733E 00
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.26747E-02-0.25685E-01    VOD= -0.12223E-02 0.34987E-01
MVOL=  0.29828E-01    MVOD=  0.35008E-01
================================================================
```

```
 RUN TLINE

LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 01 0.                ZL=  0.10000E 04 0.

FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.10209E 01-0.20774E-01    VOD=  0.10209E 01-0.20774E-01
MVOL=  0.10211E 01    MVOD=  0.10211E 01
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.27614E 01-0.11435E 01    VOD=  0.27602E 01-0.11422E 01
MVOL=  0.29888E 01    MVOD=  0.29872E 01
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.11695E 01-0.61359E 00    VOD= -0.11702E 01-0.61456E 00
MVOL=  0.13207E 01    MVOD=  0.13218E 01
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.32556E 00 0.47613E 00    VOD= -0.32553E 00 0.47594E 00
MVOL=  0.57679E 00    MVOD=  0.57664E 00
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.21143E 01 0.15460E 01    VOD= -0.21141E 01 0.15389E 01
MVOL=  0.26204E 01    MVOD=  0.26124E 01
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.14702E 01 0.17902E 00    VOD=  0.14711E 01 0.17973E 00
MVOL=  0.14811E 01    MVOD=  0.14820E 01
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.10210E 01-0.20824E-01    VOD=  0.10209E 01-0.20774E-01
MVOL=  0.10212E 01    MVOD=  0.10211E 01
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.27456E 01-0.11203E 01    VOD=  0.27602E 01-0.11422E 01
MVOL=  0.29655E 01    MVOD=  0.29872E 01
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.13797E 01-0.84376E 00    VOD= -0.11702E 01-0.61458E 00
MVOL=  0.16172E 01    MVOD=  0.13218E 01
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.23431E 00-0.11885E 00    VOD= -0.32553E 00 0.47594E 00
MVOL=  0.26273E 00    MVOD=  0.57664E 00
================================================================
```

```
 RUN TLINE

LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.50000E 02 0.                    ZL=  0.10000E 01 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.18182E-01-0.58218E-02    VOD=  0.18182E-01-0.58219E-02
MVOL=  0.19091E-01    MVOD=  0.19091E-01
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.12770E-02-0.89135E-02    VOD=  0.12776E-02-0.89133E-02
MVOL=  0.90046E-02    MVOD=  0.90044E-02
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.29660E-03-0.29316E-02    VOD= -0.29630E-03-0.29317E-02
MVOL=  0.29466E-02    MVOD=  0.29466E-02
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.24447E-04 0.69981E-03    VOD= -0.24455E-04 0.69974E-03
MVOL=  0.70024E-03    MVOD=  0.70017E-03
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.36265E-03 0.47943E-02    VOD= -0.36425E-03 0.47937E-02
MVOL=  0.48080E-02    MVOD=  0.48075E-02
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.59669E-02 0.11795E-01    VOD=  0.59613E-02 0.11796E-01
MVOL=  0.13219E-01    MVOD=  0.13217E-01
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.18173E-01-0.58358E-02    VOD=  0.18182E-01-0.58219E-02
MVOL=  0.19087E-01    MVOD=  0.19091E-01
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.13042E-02-0.89603E-02    VOD=  0.12776E-02-0.89133E-02
MVOL=  0.90547E-02    MVOD=  0.90044E-02
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.29031E-03-0.32173E-02    VOD= -0.29630E-03-0.29317E-02
MVOL=  0.32295E-02    MVOD=  0.29466E-02
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.57493E-04-0.57369E-03    VOD= -0.24455E-04 0.69974E-03
MVOL=  0.57657E-03    MVOD=  0.70017E-03
================================================================
```

```
 RUN TLINE
LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.50000E 02 0.                ZL=  0.50000E 02 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.47705E 00-0.12759E 00    VOD=  0.47705E 00-0.12759E 00
MVOL=  0.49381E 00    MVOD=  0.49381E 00
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.60646E-01-0.30743E 00    VOD=  0.60692E-01-0.30744E 00
MVOL=  0.31335E 00    MVOD=  0.31337E 00
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.23190E-01-0.12951E 00    VOD= -0.23169E-01-0.12952E 00
MVOL=  0.13157E 00    MVOD=  0.13158E 00
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.23549E-02 0.34625E-01    VOD= -0.23557E-02 0.34621E-01
MVOL=  0.34705E-01    MVOD=  0.34701E-01
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.23504E-01 0.19404E 00    VOD= -0.23598E-01 0.19397E 00
MVOL=  0.19546E 00    MVOD=  0.19540E 00
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.21917E 00 0.34005E 00    VOD=  0.21894E 00 0.34010E 00
MVOL=  0.40436E 00    MVOD=  0.40447E 00
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.47696E 00-0.12781E 00    VOD=  0.47705E 00-0.12759E 00
MVOL=  0.49379E 00    MVOD=  0.49381E 00
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.61641E-01-0.30824E 00    VOD=  0.60692E-01-0.30744E 00
MVOL=  0.31435E 00    MVOD=  0.31337E 00
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.21639E-01-0.14164E 00    VOD= -0.23169E-01-0.12952E 00
MVOL=  0.14329E 00    MVOD=  0.13158E 00
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.55443E-02-0.26049E-01    VOD= -0.23557E-02 0.34621E-01
MVOL=  0.28591E-01    MVOD=  0.34701E-01
================================================================
```

```
 RUN TLINE

 LENGHT=       1.00000    EPSILON=       1.00000
 ZO=  0.50000E 02 0.
 ZS=  0.50000E 02 0.                    ZL=  0.10000E 04 0.
 FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
 VOL=  0.92957E 00-0.20245E 00    VOD=  0.92957E 00-0.20245E 00
 MVOL=  0.95136E 00    MVOD=  0.95136E 00
 ================================================================
 FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
 VOL=  0.26375E 00-0.86246E 00    VOD=  0.26402E 00-0.86255E 00
 MVOL=  0.90189E 00    MVOD=  0.90205E 00
 ================================================================
 FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
 VOL= -0.42322E 00-0.65010E 00    VOD= -0.42321E 00-0.65058E 00
 MVOL=  0.77572E 00    MVOD=  0.77612E 00
 ================================================================
 FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
 VOL= -0.27546E 00 0.43872E 00    VOD= -0.27548E 00 0.43856E 00
 MVOL=  0.51802E 00    MVOD=  0.51790E 00
 ================================================================
 FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
 VOL= -0.22400E 00 0.80209E 00    VOD= -0.22453E 00 0.80098E 00
 MVOL=  0.83279E 00    MVOD=  0.83186E 00
 ================================================================
 FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
 VOL=  0.61185E 00 0.70422E 00    VOD=  0.61115E 00 0.70452E 00
 MVOL=  0.93289E 00    MVOD=  0.93266E 00
 ================================================================
 FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
 VOL=  0.92958E 00-0.20257E 00    VOD=  0.92957E 00-0.20245E 00
 MVOL=  0.95140E 00    MVOD=  0.95136E 00
 ================================================================
 FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
 VOL=  0.26559E 00-0.86048E 00    VOD=  0.26402E 00-0.86255E 00
 MVOL=  0.90053E 00    MVOD=  0.90205E 00
 ================================================================
 FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
 VOL= -0.39161E 00-0.74456E 00    VOD= -0.42321E 00-0.65058E 00
 MVOL=  0.84127E 00    MVOD=  0.77612E 00
 ================================================================
 FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
 VOL=  0.23764E 00-0.10132E 00    VOD= -0.27548E 00 0.43856E 00
 MVOL=  0.25834E 00    MVOD=  0.51790E 00
 ================================================================
```

```
 RUN TLINE

LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 04 0.                    ZL=  0.10000E 01 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.10209E-02-0.20774E-04    VOD=  0.10209E-02-0.20774E-04
MVOL=  0.10211E-02    MVOD=  0.10211E-02
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.27614E-02-0.11435E-02    VOD=  0.27602E-02-0.11422E-02
MVOL=  0.29888E-02    MVOD=  0.29872E-02
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.11695E-02-0.61359E-03    VOD= -0.11702E-02-0.61458E-03
MVOL=  0.13207E-02    MVOD=  0.13218E-02
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.32556E-03 0.47613E-03    VOD= -0.32558E-03 0.47594E-03
MVOL=  0.57679E-03    MVOD=  0.57664E-03
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.21143E-02 0.15480E-02    VOD= -0.21111E-02 0.15389E-02
MVOL=  0.26204E-02    MVOD=  0.26124E-02
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.14702E-02 0.17902E-03    VOD=  0.14711E-02 0.17933E-03
MVOL=  0.14811E-02    MVOD=  0.14820E-02
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.10210E-02-0.20824E-04    VOD=  0.10209E-02-0.20774E-04
MVOL=  0.10212E-02    MVOD=  0.10211E-02
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.27456E-02-0.11203E-02    VOD=  0.27602E-02-0.11422E-02
MVOL=  0.29655E-02    MVOD=  0.29872E-02
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.13797E-02-0.84378E-03    VOD= -0.11702E-02-0.61458E-03
MVOL=  0.16172E-02    MVOD=  0.13218E-02
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.23431E-03-0.11885E-03    VOD= -0.32558E-03 0.47594E-03
MVOL=  0.26273E-03    MVOD=  0.57664E-03
================================================================
```

```
 RUN TLINE

LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 04 0.                    ZL=  0.50000E 02 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.46478E-01-0.10122E-01    VOD=  0.46478E-01-0.10122E-01
MVOL=  0.47568E-01    MVOD=  0.47568E-01
================================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.13188E-01-0.43123E-01    VOD=  0.13201E-01-0.43127E-01
MVOL=  0.45094E-01    MVOD=  0.45103E-01
================================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.21161E-01-0.32505E-01    VOD= -0.21161E-01-0.32529E-01
MVOL=  0.38786E-01    MVOD=  0.38806E-01
================================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.13773E-01 0.21936E-01    VOD= -0.13774E-01 0.21928E-01
MVOL=  0.25901E-01    MVOD=  0.25895E-01
================================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.11200E-01 0.40105E-01    VOD= -0.11226E-01 0.40049E-01
MVOL=  0.41639E-01    MVOD=  0.41593E-01
================================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.30593E-01 0.35211E-01    VOD=  0.30558E-01 0.35234E-01
MVOL=  0.46645E-01    MVOD=  0.46633E-01
================================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.46479E-01-0.10123E-01    VOD=  0.46476E-01-0.10122E-01
MVOL=  0.47570E-01    MVOD=  0.47568E-01
================================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.13280E-01-0.43024E-01    VOD=  0.13201E-01-0.43127E-01
MVOL=  0.45027E-01    MVOD=  0.45103E-01
================================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.19581E-01-0.37228E-01    VOD= -0.21161E-01-0.32529E-01
MVOL=  0.42063E-01    MVOD=  0.38806E-01
================================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.11382E-01-0.50661E-02    VOD= -0.13774E-01 0.21928E-01
MVOL=  0.12917E-01    MVOD=  0.25895E-01
================================================================
```

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RUN TLINE


LENGHT=       1.00000    EPSILON=       1.00000
ZO=  0.50000E 02 0.
ZS=  0.10000E 04 0.                    ZL=  0.10000E 04 0.
FREQ.=  0.10000E 08    LEN/LAM=  0.33333E-01
VOL=  0.92062E-01-0.19643E 00    VOD=  0.92064E-01-0.19643E 00
MVOL=  0.21693E 00    MVOD=  0.21693E 00
==========================================================
FREQ.=  0.60000E 08    LEN/LAM=  0.20000E 00
VOL=  0.16850E-02-0.52204E-01    VOD=  0.16870E-02-0.52219E-01
MVOL=  0.52231E-01    MVOD=  0.52246E-01
==========================================================
FREQ.=  0.11000E 09    LEN/LAM=  0.36667E 00
VOL= -0.57492E-02-0.65257E-01    VOD= -0.57479E-02-0.65284E-01
MVOL=  0.65510E-01    MVOD=  0.65537E-01
==========================================================
FREQ.=  0.16000E 09    LEN/LAM=  0.53333E 00
VOL= -0.55847E-01 0.15951E 00    VOD= -0.55856E-01 0.15947E 00
MVOL=  0.16901E 00    MVOD=  0.16897E 00
==========================================================
FREQ.=  0.21000E 09    LEN/LAM=  0.70000E 00
VOL= -0.16657E-02 0.52007E-01    VOD= -0.16700E-02 0.51955E-01
MVOL=  0.52034E-01    MVOD=  0.51982E-01
==========================================================
FREQ.=  0.26000E 09    LEN/LAM=  0.86667E 00
VOL=  0.59715E-02 0.66510E-01    VOD=  0.59561E-02 0.66447E-01
MVOL=  0.66776E-01    MVOD=  0.66713E-01
==========================================================
FREQ.=  0.31000E 09    LEN/LAM=  0.10333E 01
VOL=  0.92009E-01-0.19639E 00    VOD=  0.92064E-01-0.19643E 00
MVOL=  0.21688E 00    MVOD=  0.21693E 00
==========================================================
FREQ.=  0.36000E 09    LEN/LAM=  0.12000E 01
VOL=  0.16970E-02-0.52129E-01    VOD=  0.16870E-02-0.52219E-01
MVOL=  0.52157E-01    MVOD=  0.52246E-01
==========================================================
FREQ.=  0.41000E 09    LEN/LAM=  0.13667E 01
VOL= -0.45436E-02-0.65501E-01    VOD= -0.57479E-02-0.65284E-01
MVOL=  0.65658E-01    MVOD=  0.65537E-01
==========================================================
FREQ.=  0.46000E 09    LEN/LAM=  0.15333E 01
VOL=  0.13067E 00 0.46820E-01    VOD= -0.55856E-01 0.15947E 00
MVOL=  0.13880E 00    MVOD=  0.16897E 00
==========================================================
```

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